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(54) **NANOELECTROMECHANICAL MEMORY CELLS AND DATA STORAGE DEVICES**

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(63) Continuation of application No. 10/453,199, filed on Jun. 2, 2003, now Pat. No. 7,095,645.

(57) **ABSTRACT**

(51) **Int. Cl.**
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Nanoelectromechanical (NEM) memory cells are provided by anchoring a conductive nanometer-scale beam (e.g., a nanotube) to a base and allowing a portion of the beam to move. A charge containment layer is provided in the vicinity of this free-moving portion. To read if a charge is stored in the charge containment layer, a charge is formed on the beam. If a charge is stored then forces between the charged beam and the charge containment layer will displace the free-moving portion of the beam. This movement may be sensed by a sense contact. Alternatively, the beam may contact a sense contact at an ambient frequency when no charge is stored. Changing the amount of charge stored may change this contact rate. The contact rate may be sensed to determine the amount of stored charge.

(52) **U.S. Cl.** **365/151**; 365/164; 365/166; 365/185.21; 977/732; 977/943

(58) **Field of Classification Search** 365/151, 365/164, 166, 185.21; 977/732, 742, 943; 257/415

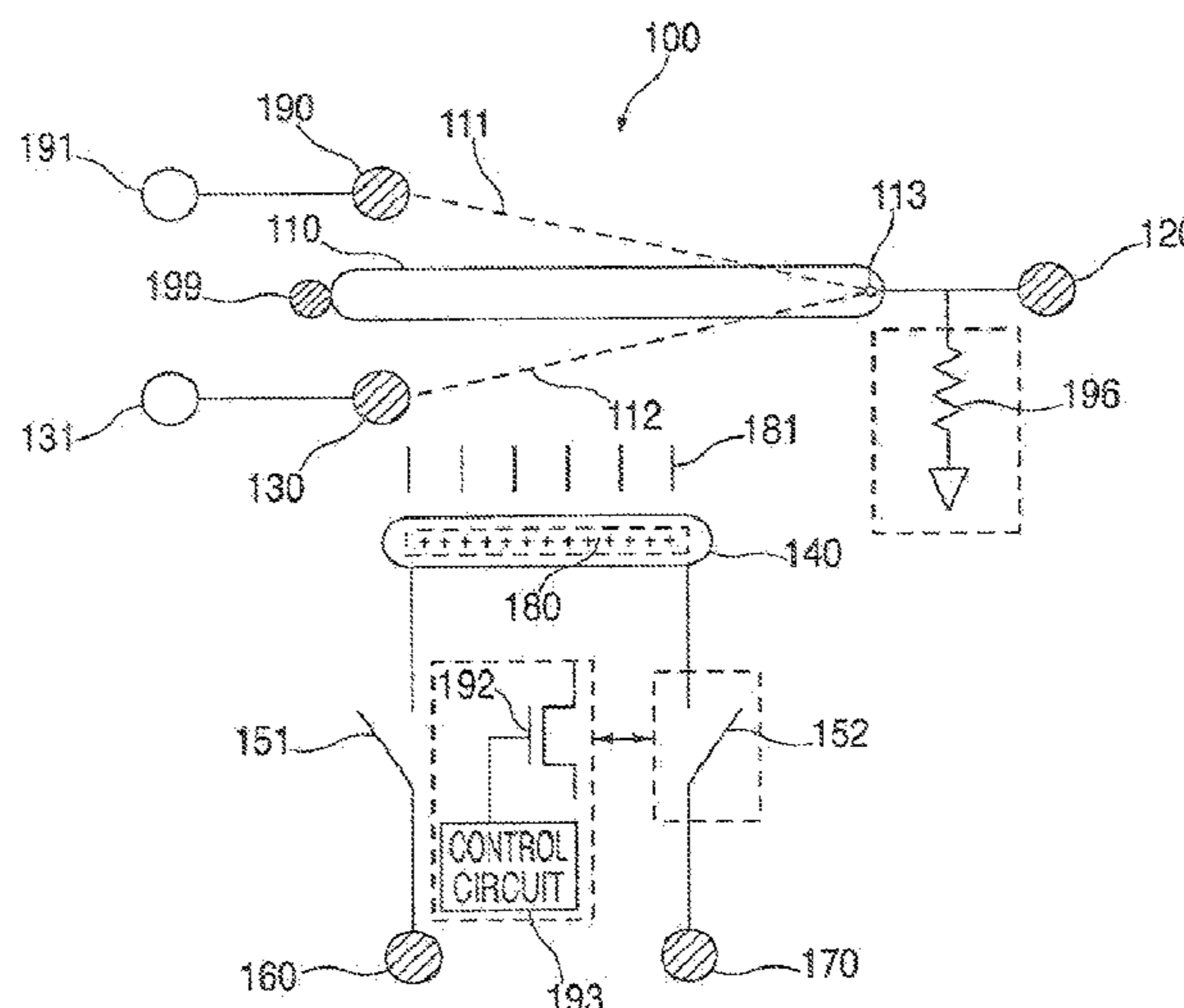
See application file for complete search history.

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33 Claims, 10 Drawing Sheets



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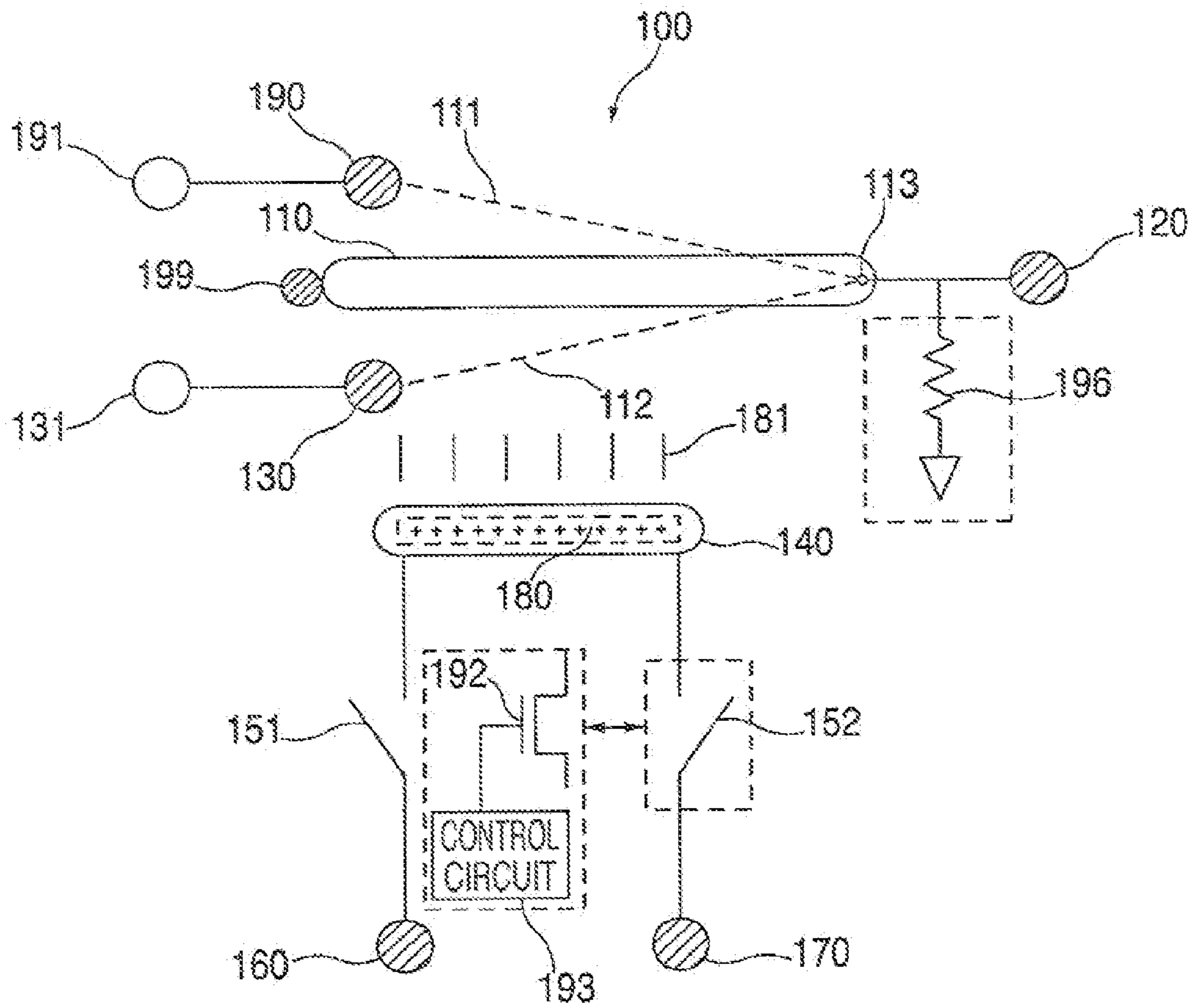


FIG. 1

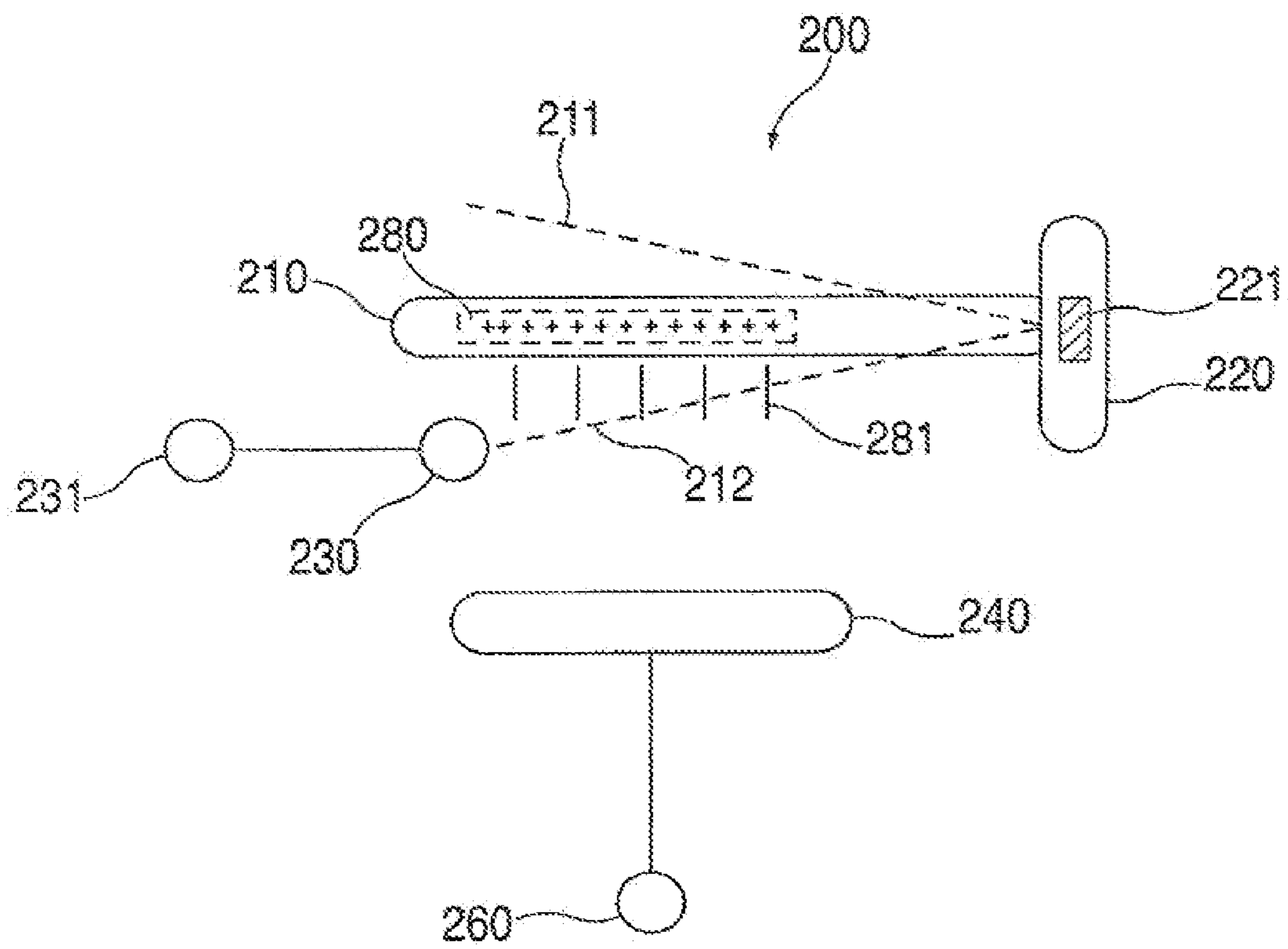
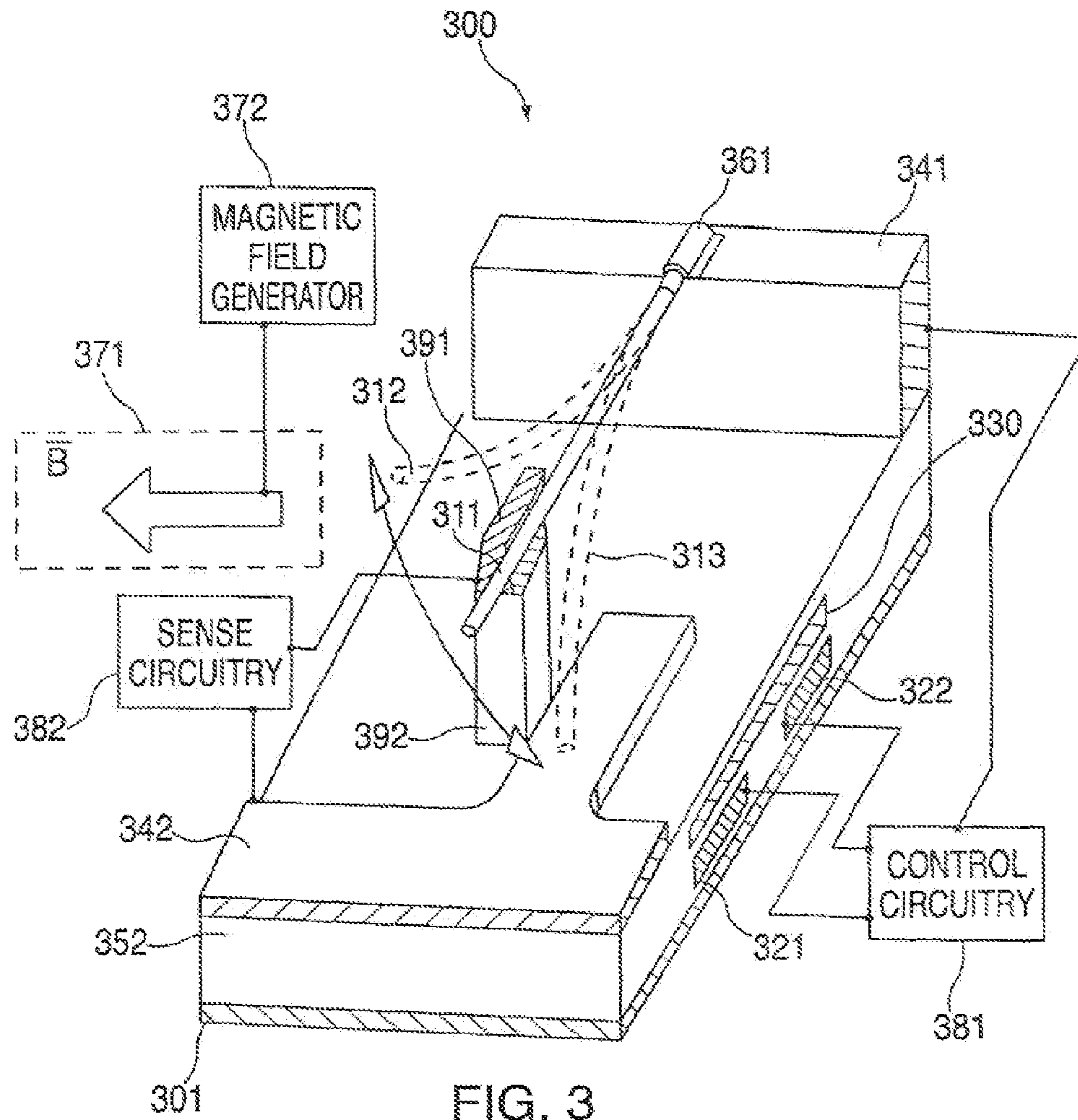


FIG. 2



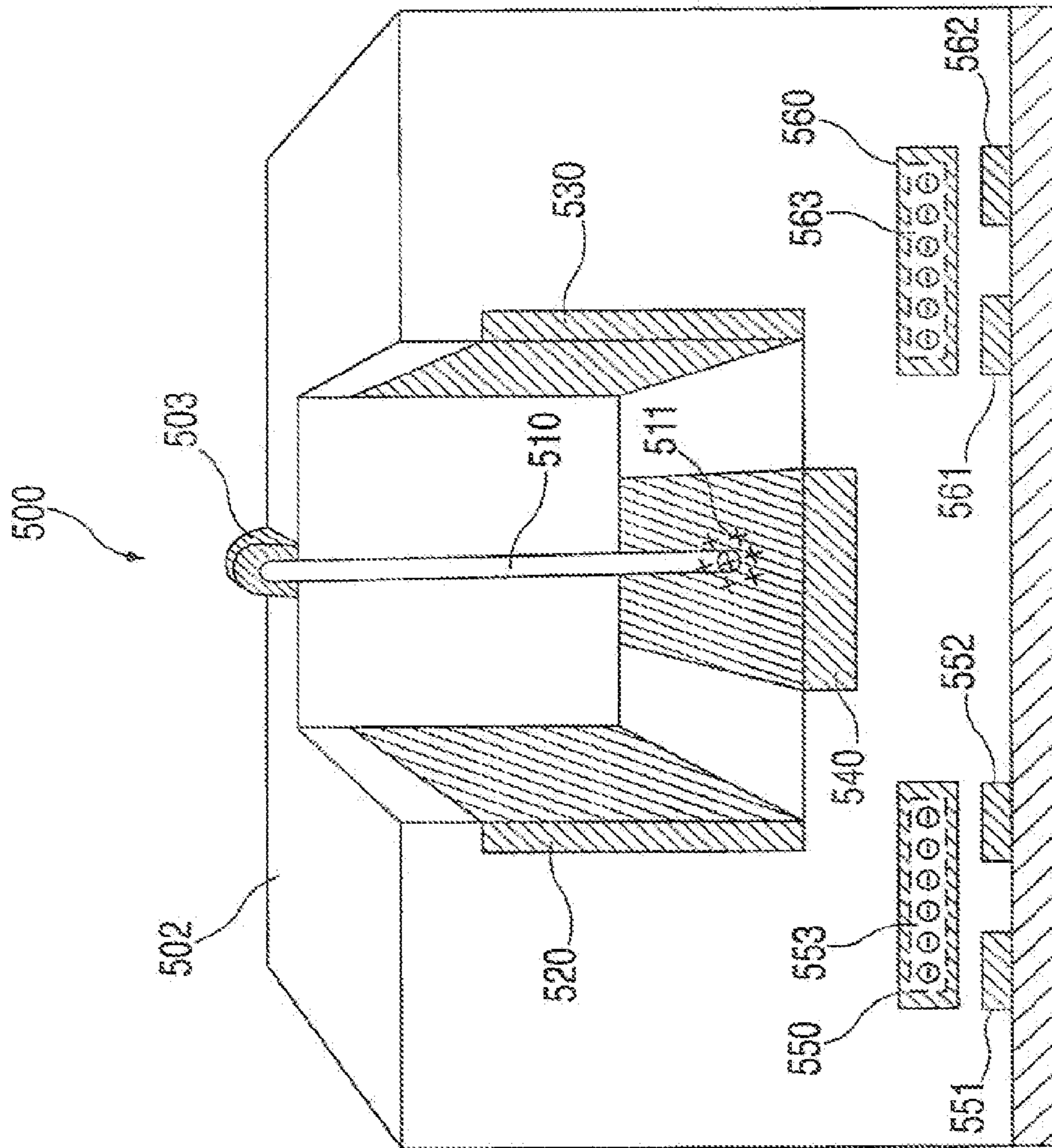


FIG. 6

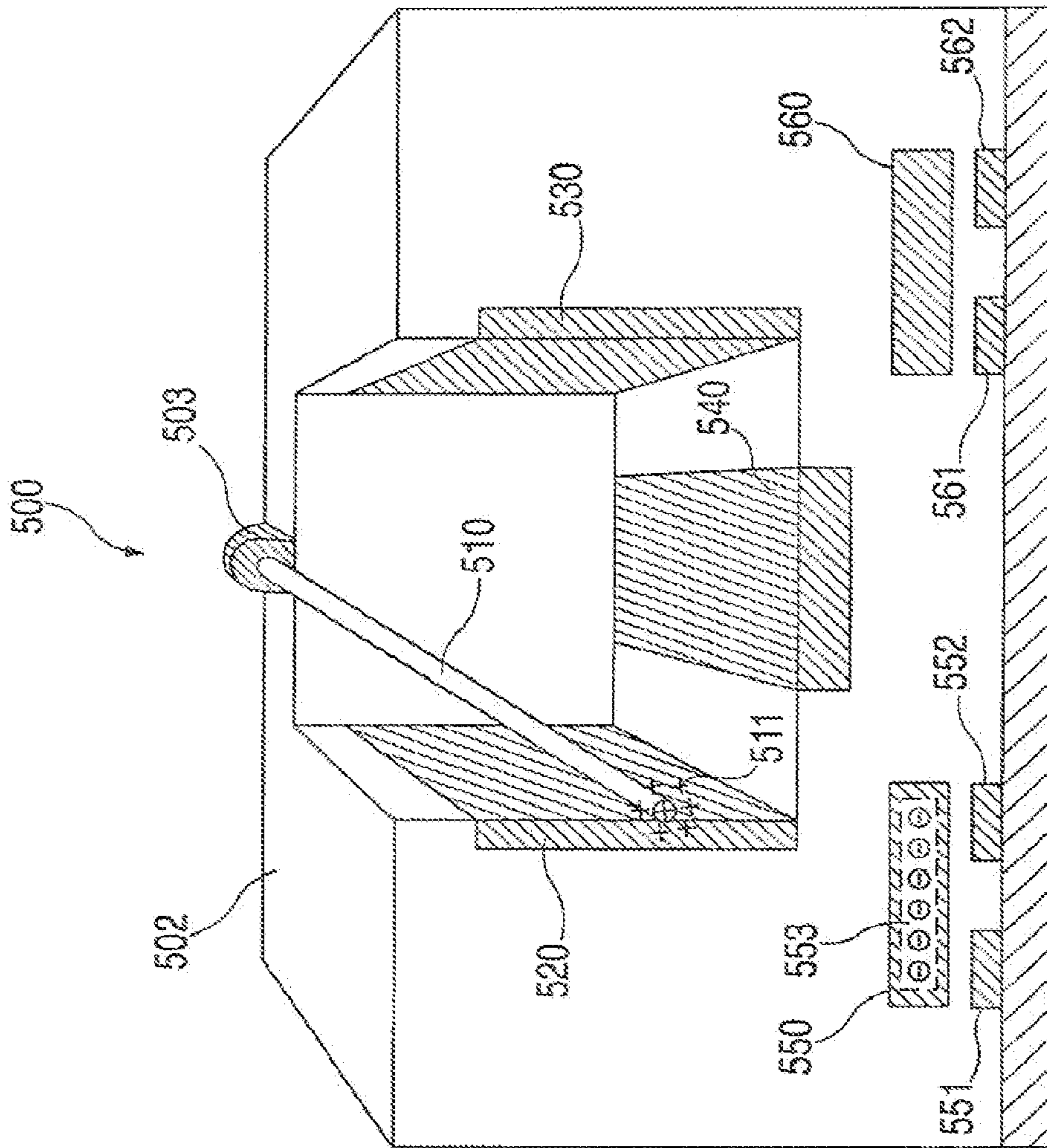


FIG. 7

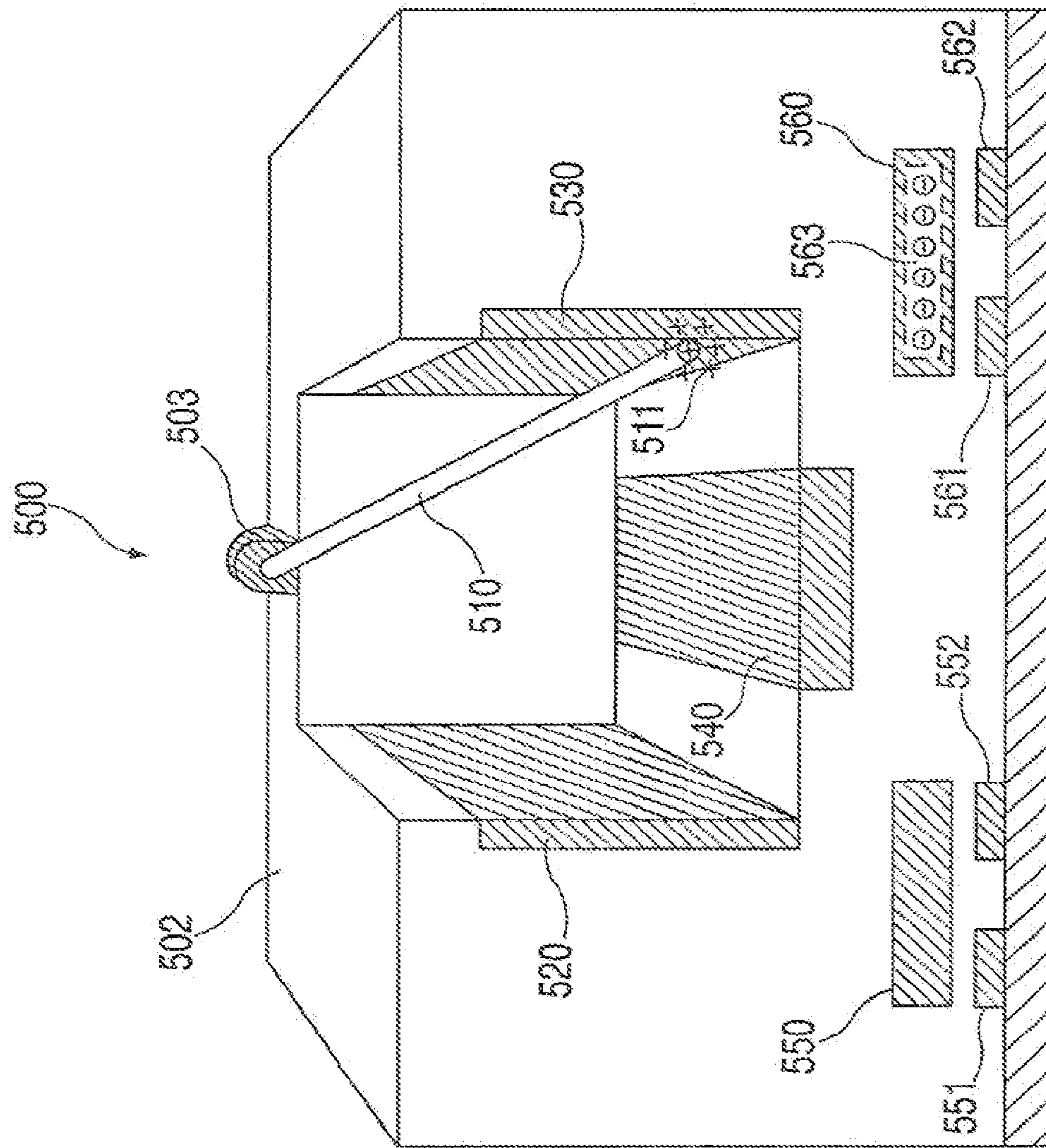
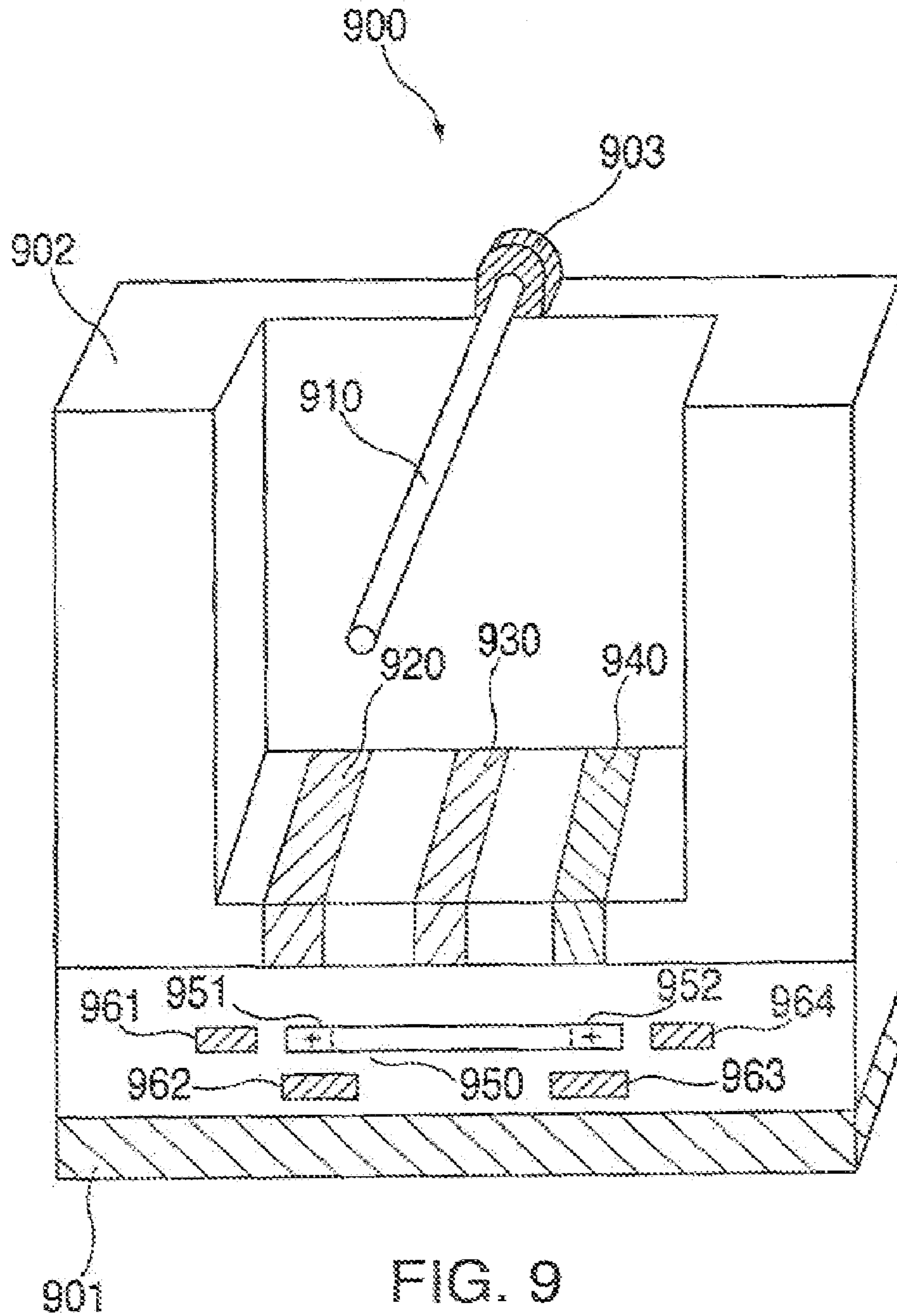


FIG. 8



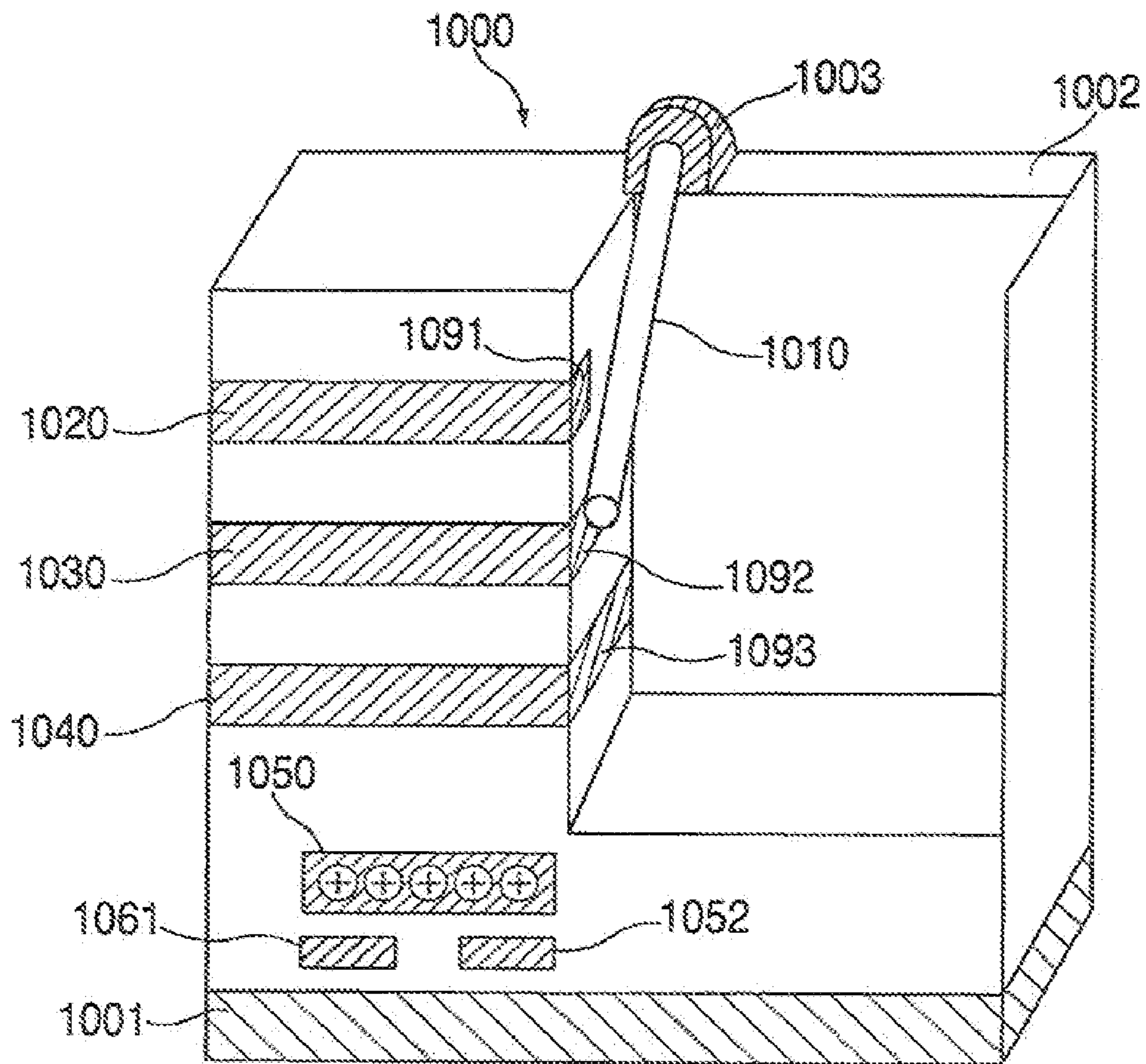


FIG. 10

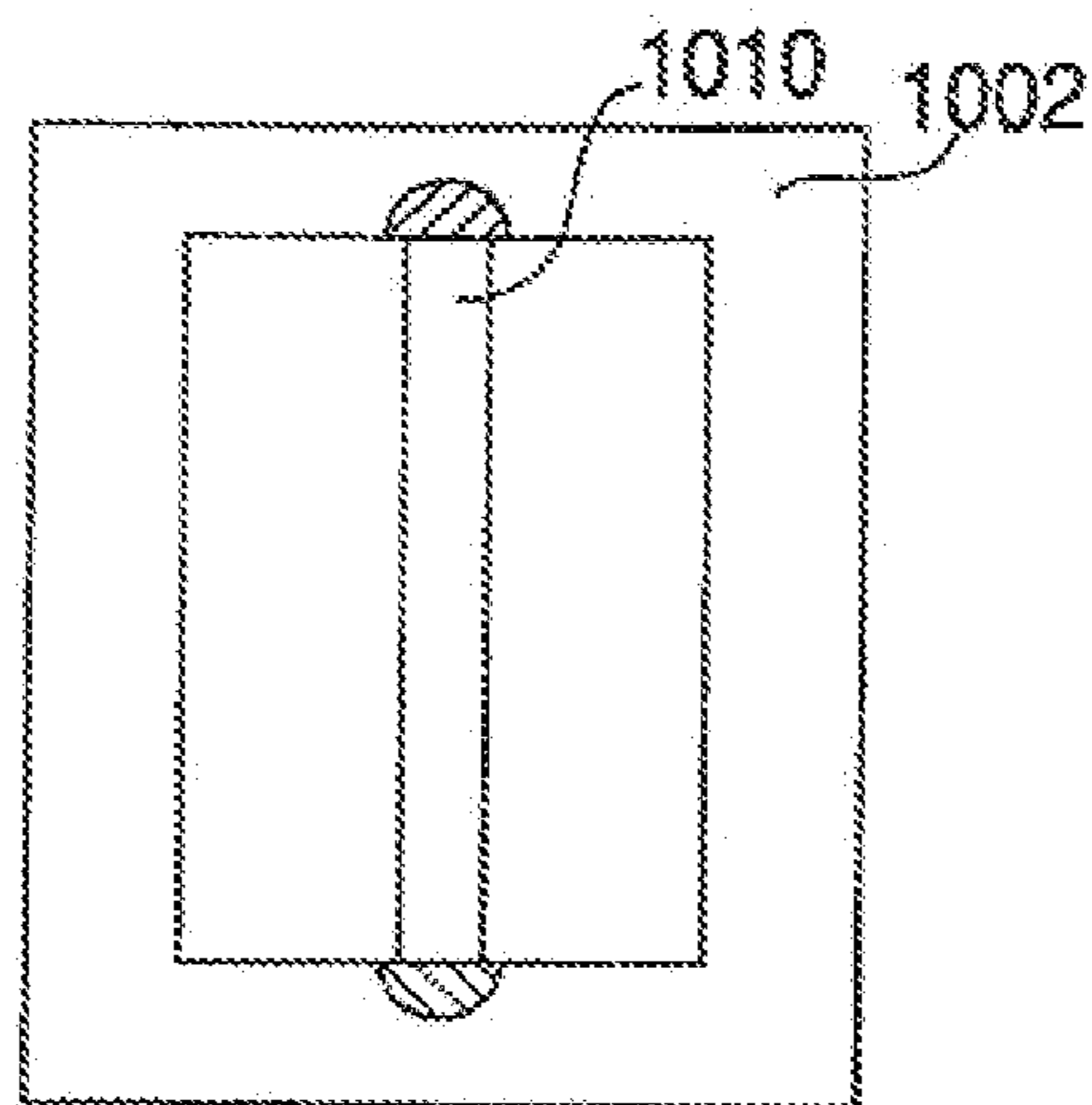


FIG. 10A

NANOELECTROMECHANICAL MEMORY CELLS AND DATA STORAGE DEVICES

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 10/453,199 filed on Jun. 2, 2003, now U.S. Pat. No. 7,095,645, which is hereby incorporated by reference herein in its entirety.

BACKGROUND OF THE INVENTION

This invention relates to memory cells. More particularly, the present invention relates to nanometer-scale memory cells that utilize nanotubes, or other nanometer-scale filaments, as a charge sensing mechanism.

Writing and erasing a charge into a charge containment layer is well known in the art. Moreover, multiple distinct charges can now be stored in separate portions of a single containment layer. Examples of such memory cells can be found, for example, in U.S. Pat. Nos. 5,768,192 and 6,011,725. However, current systems utilize transistors to determine if a charge is stored in a containment layer.

More particularly, current systems position a charge containment layer between the channel and gate of a transistor such as a metal oxide field-effect transistor (MOSFET). If a charge is stored in this charge containment layer then the turn-ON voltage of the transistor increases. In this manner, a charge is determined as being stored by applying different turn-ON voltages and determining for which turn-ON voltage the transistor turns ON. Correlating (mapping) the turn-ON voltage to a bit (e.g., a 1 if a charge is stored or a 0 if a charge is not stored) provides the functionality of a base-two memory cell; the functionality of being able to store two information states (ON and OFF) in a memory cell.

MOSFETs are deficient because they have minimum sizing limitations that generally reside in the micrometer scale. It is therefore desirable to provide a memory cell that is sized on the nanometer-scale. It is also desirable to provide nanometer-scale memory cells that can be utilized to store several bits of information, several states of information, or store a bit of information having several states (e.g., can provide a base-three or base-four information bit). It is also desirable to provide memory cells that consume low amounts of power and can store very small levels of charge.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide nanometer-scale electromechanical (NEM) memory cells. More particularly, it is an object of the present invention to provide NEM memory cells that utilize a nanometer-scale beam that is both mechanically flexible and electrically conductive, such as a nanotube, to determine if a charge is stored in a charge containment layer. Such NEM memory cells would exhibit low power consumption and have the ability to store and sense very small amounts of charge.

A nanotube is anchored to a base (either at both ends, at a single end, or between two ends) and includes a portion that is free to move. This free-moving portion is placed in the proximity of a charge containment layer. To detect if a charge of a particular polarity is stored in this charge containment layer, a READ operation is performed by applying a voltage to the nanotube. If a charge is stored in the charge containment layer then this charge will interact

with the charge on the nanotube and cause the nanotube to displace. In placing sense contacts about the nanotube in positions where the nanotube would displace to if such an event occurs, the present invention can determine the polarity of a charge, the amount of a charge, or the presence of a charge in a charge containment layer.

Take for example the instance in which a charge of a particular polarity is placed in a charge containment layer. If a charge of an opposite polarity is applied to the nanotube then the nanotube will attract to the charge containment layer due to the interaction of these opposite charge polarities. Placing a sense contact between the nanotube and this charge containment layer will preferably result, if the charges are strong enough and of opposite polarities, in a closed circuit or capacitor coupling between the nanotube and the sense contact.

In one embodiment, a HIGH AC or DC signal is applied to the nanotube in order to apply a charge to that nanotube and sense if a relatively LOW charge exists in the charge containment layer. Thus, when the nanotube couples a sense contact, this voltage will be applied to the sense contact from which an output signal, in the form of either a voltage or current signal, may be utilized by memory control circuitry.

A single charge containment layer may store multiple states or bits of data. For example, a charge containment layer may store a positive charge, a negative charge, or no charge. If a charge is written into a charge containment layer that is of the same polarity as the voltage applied to the nanotube, then the free-moving portion of the nanotube may repel. A second sense contact may be included in the location where the nanotube would repel to in order to sense this stored polarity.

Furthermore, two or more separate charges may be stored in a single charge containment layer. In this manner multiple bits (not states) may be stored, read, and erased from a single charge containment layer. Reading which charge or charges are stored in such a layer may be determined by placing multiple sense contacts around the nanotube and aligning them with where the nanotube would displace if a particular charge, or group of charges, is present in the charge containment layer. Such an embodiment would allow for more than two separate charges (bits) to be read from a single charge containment layer.

Alternatively, multiple charge containment layers may be placed around the nanotube in order to store multiple bits, or states, within a single nanotube memory cell. As in yet another alternate embodiment, the amount of charge of a certain polarity may be read by a nanotube of the present invention. For example, a LARGE positive charge will attract a nanotube exhibiting a negative charge profile. A SMALL positive charge will attract the same nanotube to a lesser degree (with respect to the LARGE positive charge). Thus, sense contacts may be placed around the nanotube according to the location of where the nanotube would be displaced if a SMALL or LARGE charge is stored in a charge containment layers.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other objects and advantages of the present invention will be apparent upon consideration of the following detailed description, taken in conjunction with accompanying drawings, in which like reference characters refer to like parts throughout, and in which:

FIG. 1 is a schematic diagram of a nanometer-scale electromechanical memory cell constructed in accordance with the principles of the present invention;

FIG. 2 is a schematic diagram of another nanometer-scale electromechanical memory cell constructed in accordance with the principles of the present invention;

FIG. 3 is a three-dimensional perspective view of one embodiment of the nanometer-scale electromechanical memory cell from FIG. 1 constructed in accordance with the principles of the present invention;

FIG. 4 is a three-dimensional perspective view of one embodiment of the nanometer-scale electromechanical memory cell of FIG. 2 constructed in accordance with the principles of the present invention;

FIG. 5 is a three-dimensional perspective view of another nanometer-scale electromechanical memory cell constructed in accordance with the principle of the present invention;

FIGS. 6-8 are three-dimensional perspective views of the functionality of one embodiment of the memory cell from FIG. 5 constructed in accordance with the principles of the present invention;

FIG. 9 is a three-dimensional perspective view of another nanometer-scale electromechanical memory cell constructed in accordance with the principles of the present invention;

FIG. 10 is a three-dimensional perspective view of yet another nanometer-scale electromechanical memory cell constructed in accordance with the principles of the present invention; and

FIG. 10A is a top-down view of yet another nanometer-scale electromechanical memory cell constructed in accordance with the principles of the present invention.

DETAILED DESCRIPTION OF THE DRAWINGS

Turning first to FIG. 1, NEM memory cell 100 is shown that includes a nanotube 110, anchored at point 113, and a charge containment layer 140. Nanotube 110 is supplied a voltage by contact 120 and is free to move to positions 111 and 112.

Persons skilled in the art will appreciate that nanotube 110 is more generally a nanometer-scale beam. Nanotube 110 may be any variety of mechanically flexible and electrically conductive molecules, filament, or bonded group of molecules, and still coincide with the spirit of the invention. Furthermore, anchor point 113 may be included anywhere on nanotube 110 as well as in multiple locations. For example, both ends of nanotube 110 may be anchored such that a jump-rope movement is provided by a middle, free-moving, portion of such a nanotube. As per another example, the middle portion of the nanotube may be anchored such that both ends of the nanotube are free-to-move.

Charge containment layer 140 may be utilized to store charge profile 180 such that, preferably, electric field vectors 181 are provided. Writing charge profile 180 into and erasing charge profile 180 from charge containment layer 140 is preferably controlled by control devices 151 and 152 which, in turn, control when the voltage signals applied to contacts 160 and 170 electrically couple charge containment layer 140. Control devices 151 and 152 may be, for example, transistors (e.g., nanotube-based nanometer-scale transistors) or diodes.

In preferred embodiments, control devices 151 and 152 are isolation layers (e.g., oxide or non-conductive layers) formed between charge containment layer 140 and contacts 160 and 170, respectively. Such isolation layers are preferably configured such that particular voltages applied to contact 160 and/or 170 can overcome the isolation characteristics of the control device and store/remove a charge from charge containment layer 140. Such isolation layers are also preferably configured such that a stored charge (e.g.,

charge profile 180) generally does not overcome the isolation characteristics of the control device.

In this manner, charge profile 180 may generally be written/stored into charge containment layer 140 by performing a WRITE operation. Such a WRITE operation may be accomplished by applying, for example, a voltage signal of the desired polarity to charge containment layer 140. If control device 151 is utilized as an isolation layer then the voltage supplied to contact 160 is preferably large enough to overcome this isolation.

More than one control device may be utilized in a WRITE operation. For example, control device 152 may aid control device 151 in trapping charge profile 180 in charge containment layer 140. In this example, control device 151 may be utilized as a pulling force by allowing unwanted charges (e.g., charges of a polarity opposite that of a desired charge profile 180) to escape by providing a signal that attracts these unwanted charges.

Manipulating the strength and duration of the voltage or current signals supplied to contacts 160 and/or 170 may only affect the speed and accuracy of trapping charge profile 180, but may also be utilized to store charge profiles 180 that exhibit electric field vectors 181 having different and distinguishable strengths/intensities. For example, a LARGE density of positive charges in charge containment layer 180 will preferably create LARGE positive electric field 181. However, a relatively SMALL density of positive charges in charge containment layer 180 will preferably create SMALL positive electrostatic forces 181.

ERASE operations may be conducted in a manner similar to the WRITE operations described above. For example, if a non-neutral charge profile 180 exists in charge containment layer 140 then a hot-hole or electron injection procedure may be undertaken by neutralizing charge profile 180 by injecting an amount of charge having an opposite polarity. A TEST operation may also be included to determine when charge profile 180 is neutral or over-erased.

Persons skilled in the art will appreciate that multiple different types of WRITE/ERASE operations may be performed on containment layer 140 in order to store, modify, or remove charge profile 180 from charge containment layer 140. For example, if control devices 151 or 152 are transistors, then an ERASE operation may be performed by grounding-out charge profile 180 by electrically coupling a ground signal to charge containment layer 140. Such an operation is an example of an operation in which over-erasure of charge containment layer 140 will, generally, not occur. All ERASE/WRITE/TEST operations fall within the spirit of the present invention.

Charge profile 180 may be read by utilizing nanotube 110 and by performing a READ operation. Generally, a READ operation occurs as follows. A voltage (either AC or DC) is applied to nanotube 110 at contact 120 and the resultant charges that are provided in nanotube 110 may interact with a non-neutral charge profile 180.

For example, if charge profile 180 has the same polarity as the voltage, or charge generator, applied to nanotube 110 then nanotube 110 will generally repel. If nanotube 110 is repelled far enough then nanotube 110 will electrically couple (e.g., create a galvanic connection or a capacitive coupling) at sense contact 190 and an output signal 191 will be provided that is representative of the signal applied to contact 120.

Charge profile 180 may also be read by determining a contact rate, or change in contact rate, between nanotube 110 and a sense contact. For example, when charge profile 180 contains a neutral (e.g., zero) charge, nanotube 110 prefer-

ably contacts a sense contact (e.g., sense contact 190) at, or about, an ambient rate due to the thermal vibrations of the environment that memory cell 100 is located in. More particularly, nanotube 110 may oscillate according to surrounding temperatures. Thus, if charge profile 180 provides attracting electric field vectors 181 to nanotube 110 then the contact rate between nanotube 110 and the sense contact will increase. In this manner, the contact rate between nanotube 110 and a particular sense contact is proportional to the characteristics of charge profile 180.

As per another example, if it is desirable to READ if a net positive charge is stored in charge containment layer 180 then a negative voltage may be applied to nanotube 110 via contact 120. If a net-positive charge is stored in charge containment layer 140 then nanotube 110 will attract to charge containment layer 180. If charge profile 180 is of the appropriate polarity and strong enough then nanotube 110 preferably electrically couples to sense contact 130. Because a voltage is induced on nanotube 110, sense contact 130 will, if electrically coupled to nanotube 110, provide output signal 131 that is representative of the signal applied to contact 120. If an appropriate charge profile 180 is not stored in charge containment layer 180 then there is not an appropriate sense signal 131 on sense contact 130.

Thus, to-reiterate, a READ operation is generally accomplished as follows. A charge of a particular polarity is formed on nanotube 110. A sense contact is placed about nanotube 110 such that if a particular charge profile 180 is stored in charge containment layer 180 then electric field vectors 181 will interact with the electric field of nanotube 110 and displace nanotube 110 toward the sense contact. In this manner the sense contact determines, by providing an output signal, if the particular charge profile is stored in charge containment layer 140 by determining if a sense signal is obtained for a period of time that nanotube 110 is charged by signals applied to contact 120. As will be described in more detail later, output signals may also be obtained through, or about, contact 120 and sense signals may be representative of a frequency of electrical interactions between nanotube 110 and a sense contact.

Persons skilled in the art will appreciate that output signals 131 and 191 can be translated into a logical "1" or "0". For example, if a net-negative charge is impressed on nanotube 110, sense contact 130 can determine if a net-positive charge is stored in charge containment layer 140. A logical "1" or "0" may be associated to these two states such that charge containment layer 140 can store a bit of information. For example, if sense contact 130 detects a net-positive charge, a logical "1" may be registered. If sense contact 130 does not detect a net-positive charge, a logical "0" may be recognized.

Persons skilled in the art will appreciate that memory cell 100 may be configured to store multiple states and bits of information. For example, if both sense contacts 130 and 190 are included, then three states may be stored (e.g., net-positive, net-negative, and neutral charge containment layer 140). If three states are stored by NEM memory cell 100 then NEM memory cell 100 could be considered as storing a single base-three bit. Base-three tailored controllers, encoders, and multiplexers would preferably be included in such an embodiment. Embodiments which store multiple states, and are configured differently than NEM memory cell 100 to store multiple states, are described later in the description.

As mentioned above, a TEST operation may be included in NEM memory cell 100. Such a TEST operation may included utilized to check if charge profile 180 is neutral,

under-erased, or over-erased. Such an operation may be beneficial, for example, after an ERASE operation or as a stage/stages during a multiple-stage ERASE operation.

Sense contact 199 may included around the resting location of nanotube 110 and utilized in one embodiment of a TEST operation. Sense contact 199 couples to nanotube 110 when charge profile 180 is neutral and nanotube 110 is in a resting location. An output signal from sense contact 199 may be provided, for example, by providing a voltage signal to contact 120.

Persons skilled in the art will appreciate that thermal vibrations around nanotube 110 may cause nanotube 110 to vibrate around a resting location. In this manner, nanotube 110 may contact a sense contact of memory cell 100 even when charge profile 180 does not provide any electrostatic force vectors 181. Thus, nanotube 110 may not continuously contact sense contact 199 but contact sense contact 199 at a particular frequency, or in a range of particular frequencies, when no charge is contained in charge profile 180.

If a TEST operation is executed after an ERASE operation and the TEST operation fails (e.g., sense contact 199 does not sense a signal representative of the signal applied to nanotube 110) then a READ operation may be utilized to determine the polarity of charge containment layer 140. According to the results of this READ operation, an appropriate ERASE operation may be performed followed by yet another TEST operation. This routine may continue until the TEST operation succeeds.

Persons skilled in the art will appreciate that sense contact 199 is not needed in order to perform a TEST operation. Alternatively, relatively very LARGE signals may be applied to contact 120 to sense even very SMALL charge profiles 180 in charge containment layer 140. In this manner, the strength of the signal applied to contact 120 that is needed to couple nanotube 110 with a sense contact is representative of the amount of charge stored in charge containment layer 140.

Persons skilled in the art will appreciate that in some embodiments a TEST operation may not be needed, or may not be desired because it will not be possible to over-erase charge containment layer 140 (or any over-erasure of charge containment layer 140 is negligible even if over-erasure occurs, for example, thousands of times).

Control circuitry 193 may be utilized to perform various READ, WRITE, and ERASE operations to multiple memory cells 100. Operations on memory cells of the present invention may be executed on batches of memory cells (e.g., array sectors) or single memory cells. Encoders/decoders and Multiplexers/dividers (not shown) may also be included to help route, manipulate, select, and control the signals of one or more memory cells 100.

Thermal characteristics of the environment about NEM memory cell 100 may cause nanotube 110 to vibrate about anchor point 113. If these thermal vibrations are strong enough, or the sense contacts are close enough to nanotube 110, then nanotube 110 may couple with sense contacts 130 at, or in a range associated with, an ambient frequency. For example, regardless of the strength and polarity of charge profile 180, nanotube may couple with contact 130, for example, 100 times a second if no charge is imposed on nanotube 110. However, if charge profile 180 is non-neutral and nanotube 110 is supplied with a charge profile having an opposite polarity to charge profile 180 then the number of contacts between nanotube 110 and contact 130 will increase to, for example, 1000 times a second. In this manner, the strength and polarity of charge profile 140 may be determined not only by the location in which nanotube 110 is

displaced, but the number of times (frequency) that nanotube **110** contacts (or capacitively couples) a sense contact during a period of time. Furthering this example, a SMALL charge profile **180** may be distinguished from a LARGE charge profile **180** because a LARGE charge profile **180** will preferably contact sense contact **130** at a different frequency than if a SMALL charge profile **180** is stored.

Persons skilled in the art will appreciate that other structures and electrical characteristics may be included, and advantageously utilized, in NEM memory cell **100**. For example, a magnetic field (not shown) may be included in memory cell **100** such that a Lorentz force is created when nanotube **110** is electrically coupled to a sense contact and current flows through nanotube **110**. Nanotube **110** may be tube-shaped (e.g., hollow) or rod-shaped (e.g., solid).

Alternatively, memory cell **100** can be configured such that current flows from sense contact **130** to contact **120** via nanotube **110**. Moreover, contact **120** may be utilized as a sense contact. For example, if resistor **196** is included then no current will flow through resistor **196** when nanotube **110** is not electrically coupled to sense contact **130** (open circuit conditions). However, an amount of current will preferably flow through resistor **196** when nanotube **110** couples contact **130** and current flows through nanotube **110** (closed circuit conditions). Thus, a sense signal may be obtained from sense contact **120** by way of, for example, resistor **196**.

As stated above, control device **152** may be a transistor. More particularly, control device **152** may be transistor **192**. Transistor **192** may be configured to have, for example, a collector terminal (or source terminal) coupled to charge containment layer **140** and an emitter terminal (or drain terminal) coupled to a control contact such as contact **170**. Persons skilled in the art will appreciate that the emitter terminal of transistor **192** may alternatively be coupled to charge containment layer **140** and the collector terminal of transistor **192** may be coupled to a control contact. Furthermore, the base of transistor **192** may be coupled to control circuitry **193**. In such an embodiment, the control contact may be coupled to, for example, a voltage source or a ground terminal such that control circuitry **193** controls when this voltage source, or ground terminal, is coupled to charge containment layer **140**.

FIG. **2** shows memory cell **200** in which nanotube **210** is utilized as a charge containment device. Nanotube **210** is preferably filled, either substantially or partially, with a charge containment layer or filaments of a charge containment layer. Nanotube **210** is isolated by isolation layer **220**, to which nanotube **210** is also preferably anchored. Operations on nanotube **210** may be executed by signals **231** applied to contact **230** and signals applied to contact **221**. Charge member layer **240** may also be included and have a charge profile provided by contact **260**. Similar to NEM memory cell **100**, a control device may be included between contact **260** and containment layer **240**.

Memory cell **200** generally operates as follows. A voltage signal is supplied to charge member layer **240** by contact **260** such that if an opposite polarity of charge exists in nanotube **210** then nanotube **210** will electrically couple contact **230** and sense signal **231** will be obtained from contact **230** that is representative of charge profile **280**. Persons skilled in the art will appreciate that elements of, for example, NEM memory cell **100** may be included in NEM memory cell **200**. For example, a second sense contact may be included above nanotube **210** to sense a repelling force created when charge profile **280** has the same polarity as the polarity of charge member layer **240**. In one WRITE operation, a charge or hole may be injected into nanotube **210** by

contact **221**. A more detailed description of the operation of memory cell **200** is discussed in accordance with NEM memory cell **400** of FIG. **4**.

FIG. **3** shows NEM memory cell **300** which is one embodiment constructed from the principles of NEM memory cell **100** of FIG. **1**. Nanotube **311** is anchored to base **301** and is free to move between positions **312** and **313**. In particular, nanotube **311** is anchored to contact **341** via retaining member **361**. Contact **341** is then anchored to base **301** via isolation layer **352**.

As in NEM memory cell **100** of FIG. **1**, a charge containment layer, charge containment layer **330**, is included in NEM memory cell **300**. Contacts **321** and **322** may be utilized to perform WRITE and ERASE operations. Persons skilled in the art will appreciate that control devices **151** and **152** of FIG. **1** are included in NEM memory cell **300** as the portions of isolation **352** between charge containment layer **330** and contacts **321** and **322**, respectively.

Generally, if a charge is stored in charge containment layer **330** that has an opposite polarity then the charge induced on nanotube **311**, and if the charges are sufficiently strong, then nanotube **311** may electrically couple to sense contact **342**. Magnetic field **371** may be applied, or selectively applied, to memory cell **300** such that if current flows through nanotube **311** then nanotube **311** will stay coupled to sense contact **342** because of the Lorentz forces created by magnetic field **371**.

Persons skilled in the art will appreciate that in one embodiment, magnetic field **371** may be selectively turned ON when a READ operation is performed. As a result of selectively turning ON magnetic field **371** and the voltage source applied to contact **341**, power consumption may be reduced.

Similarly, a voltage signal may be applied to contact **341** only when a READ operation is performed because, when it is not desirable to READ charge containment layer **330**, applying a signal to layer **341** may not provide any functionality. However, persons skilled in the art will appreciate that the opposite may be true. For example, if control circuitry is trying to read a memory cell in a sector in which memory cell **300** is located then all the memory cells of this location may be provided a signal to layer **341**, but only the sense contact for the desired memory cell will be read. Doing so would decrease the amount of circuit complexity that may be included to provide signals to layer **341**.

To employ the TEST operation described above, contact **391** may be placed about the resting location of nanotube **311** and anchored by non-conductive layer **392**. Contact **391** may also be placed, for example, above nanotube **311** and on the resting location of nanotube **311** so nanotube **311** usually couples with contact **391** when nanotube **311** is in a resting position (the position nanotube **311** is shown as being in for FIG. **3**). In this manner, contact **391** preferably forms a portion of a ceiling (not shown) such that nanotube **311** does not touch contact **391** and isolation layer **392** as nanotube **311** descends towards sense contact **342**. Thus, wear to memory cell **300** is reduced.

To reiterate, any number of sense contacts (e.g., sense contacts **342**) may be placed anywhere about charge containment layer **330** and configured to provide functionality in accordance with the principles of the present invention. Furthermore, one or more contacts (e.g., contacts **321** and **322**) may also be utilized to perform the operations on memory cell **300** and may be placed in a variety of locations around one or more charge containment layers (e.g., charge containment layer **330**). Such configurations are within the

spirit of the present invention. Additional embodiments further illustrating these principles are discussed below in more detail.

Persons skilled in the art will appreciate that memory cell **300** can be READ numerous times without having to be RE-WRITTEN after each READ operation. This is an advantage over numerous conventional micrometer-scale memory cells that require a charge to be RE-WRITTEN into a charge containment layer if the charge containment layer is READ and determined to have contained a charge. This is because such memory cells remove a charge from a charge containment layer in order to read that charge.

Sense circuitry **382** and control circuitry **381** may also be included in NEM memory cell **300**. Sense circuitry **382** may be, for example, coupled to contact **342** to sense the electrical signals provided from control circuitry **381** to contact **341** when nanotube **311** is electrically coupled to contact **342**. Sense circuitry **382** may also be, for example, coupled to contact **391** in order to sense when nanotube **311** is electrically coupled to contact **391** (e.g., when the electrical signals provided to contact **341** flow through nanotube **311** to contact **391** or vice versa). Control circuitry **381** may be coupled, for example, to WRITE/ERASE contacts **321** and **322** in order to provide appropriate electrical signals to charge containment layer **330**. Persons skilled in the art will appreciate that sense circuitry **382** and control circuitry **381** may be coupled to other components of NEM memory cell **300**. For example, control circuitry **381** may be coupled to contact **342** and sense circuitry **382** may be coupled to contact **341**. Additionally, magnetic field **371** is preferably provided by magnetic field generator **372**.

Persons skilled in the art will appreciate that nanotube **311** is generally fixed to base **301** by a mounting member. Such a mounting member may include, for example, any number of components that are placed between nanotube **311** and base member **301**. For example, nanotube **311** may be mounted to base **301** by contact **341** or by both contact **341** and isolation layer **352**. Preferably, nanotube **311** is fixed to base **301** by mounting components such that a portion of nanotube **311** does not move with respect to base **301**. Furthermore, these mounting components also preferably provide at least one other portion of nanotube **311** that is free to move with respect to base **301**.

FIG. **4** shows NEM memory cell **400** which includes nanotube **411**. In the preferred embodiment, the middle of nanotube **411** is attached to base member **404** such that the ends of nanotube **411** are free to move. Nanotube **411** may be stabilized at its center by, for example, isolation layers **431** or **401**.

Nanotube **411** may be fabricated to contain molecules **421**. Molecules **421** may exhibit charge containment characteristics. For example, molecules **421** may be nitride-oxide or dielectric molecules. As a result of molecules **421** being located inside of nanotube **411**, a charge that is deposited into nanotube **411** may be captured. As a result, a nanotube-based memory cell may be constructed in accordance with the principles of the present invention.

In NEM Memory cell **400**, a WRITE operation may occur as follows. Nanotube **411** is manipulated by charge members **402** and **403** into either position **413** or **415** to create electrical connections with either contact layers **405** or **406**, respectively. If, for example, nanotube **411** is attracted to charge member **402** such that nanotube **411** electrically couples with contact **405** then molecules **421** may become charged with the signal applied to contact **405** at that time. As per an alternative, nanotube **411** may be charged by

placing a large voltage signal on contact layer **432** such that the signal seeps through isolation layer **431**.

In NEM memory cell **400**, a READ operation may occur as follows. An “attracting” charge (e.g., charge opposite the charge placed in nanotube **411** during a WRITE operation) may be placed on charge member layer **402** (and/or charge member **403**). Contacts **405** and **406** may then be used to sense when nanotube **411** comes into contact with contacts **405** and **406**. If zero or a LOW charge (e.g., logical 0) is present in nanotube **411** than the amount of charge placed on charge members **402** and **403** will be relatively large when creating an electrical connection with contacts **405** and **406**. If a HIGH charge (e.g., logical 1) is present in nanotube **411**, than the amount of charge placed on charge members **402** and **403** will be relatively small when creating an electrical connection with contacts **405** and **406**. Thus, as per this example, NEM memory cell **400** may be read by measuring the amount of charge needed on charge members **402** and **403** to create an electrical connection between nanotube **411** and electrical contacts **405** and **406**.

Persons skilled in the art will appreciate that specific amounts of charge may be stored and distinguished from each other in nanotube **411**. In this example, the amount of charge required to be applied to charge members **402** and **403** to sense nanotube **411** by contacts **405** and **406** may be utilized in determining the amount of charge stored in nanotube **411**. As a result, multiple states may be stored and distinguished as nanotube **411** holds multiple charge profiles (e.g., 4 measurable states allows nanotube **411** to store 2 bits). Persons skilled in the art will appreciate that the READ operation described above may result in a discharging of the charge stored in nanotube **411**. However, by including two free-moving ends on nanotube **411**, nanotube **411** may be written as it is being read (i.e. simultaneous read/write operation). For example, NEM memory cell **400** may be constructed such that charge members **402** and **403** are coupled together. For example, contact **405** may be used to sense a charge in nanotube **411**. Contact **406** may then be used to write a charge to nanotube **411**. In preferred embodiments, the amount of charge applied to contact **406** may be proportional to the amount of charge applied to charge members **402** and **403**. As a result, multiple states may be simultaneously written and read into nanotube **411**. Yet, it may be necessary to uncouple the “reading” end of NEM memory cell **400** before the “writing” end of NEM memory cell **400** is uncoupled in order to ensure that a charge is adequately stored on nanotube **411**. Thus, depending on the application, charge members **402** and **403** may be independent and electrically isolated from one another. NEM memory cell **400** may also be simultaneously written and re-written to by contact **432**.

A NEM memory cell may also be embodied with a nanotube having only a single free-moving end. More particularly, nanotube **411** may also be attached at one end to base member **404** via isolation layer **401** such that, for example, only charge member **402** and contact **405** are needed. This example would provide a MEM memory cell **400** that is similar to the structure illustrated in FIG. **4** to the left of line **451**. Contact **405** would preferably be utilized as both a sensing and writing contact. However, contact **432** may still be utilized to write or re-write nanotube **411**.

As an alternative to memory cells, the principles of the present invention may be utilized to construct memory components (e.g., memory latches) from nanotube-based inverters.

FIG. **5** shows memory cell **500** that includes three sense contacts **520**, **530**, and **540** and two charge containment

layers **550** and **560**. A single nanotube **510** is utilized to read both charge containment layers **550** and **560**. As a result, memory cell **500** may actually be seen as providing the functionality of two memory cells while only including a single nanotube **510**.

Charge containment layer **550** may be written to, or erased by, contacts **551** and **552**. Similarly, charge containment layer **560** may be written to, or erased by, contacts **561** and **562**. Nanotube **510** is anchored to base **502** by conductive retainer **503**. Non-conductive layer **502** is utilized as a memory cell sculpting and component isolating layer. FIG. **5** shows an example of how memory cell **500** may operate when no net charges exist in either charge containment layers **550** or **560**. In this embodiment, nanotube **510** is in a resting location and is isolated from sense contacts **520**, **530**, and **540**. If a charge is applied to nanotube **510** then nanotube **510** will generally not be substantially dislocated because neither a repelling force or an attracting force will be provided by charge containment layers **550** and **560**. FIGS. **6-8** show some of the various instances when charge containment layers **550** and **560** provide displacement in the location of nanotube **510**.

FIG. **6** shows memory cell **500** when a net-negative charge is stored in both charge containment layers **550** and **560** and a net-positive charge **511** is applied to nanotube **510** via conducting retainer **503**. In particular, negative charge profiles **553** and **563** preferably generate a downward motion that causes nanotube **510** to electrically couple to sense contact **540**, thus providing a signal, representative of charge containment layers **550** and **560** having stored charges, to control circuitry (not shown). Each of sense contacts **520**, **540**, and **530** (or the signals associated with nanotube coupling to sense contacts **520**, **540**, and **540**) may be mapped to a state of information. Thus, memory cell **500** may store two-bits (four states) of information. A magnetic field may also be either permanently imposed on memory cell **500** or selectively imposed on memory cell **500** according to the signals applied to conductive retainer **503**.

FIG. **6** shows memory cell **500** when charge profile **553** and charge profile **563** is stored in charge containment layers **550** and **560**, respectively. In this instance, if an opposite polarity of charge is provided at the end of nanotube **510**, an attracting force preferably causes nanotube **510** to couple sense contact **540**.

FIG. **7** shows memory cell **500** when only charge profile **553** is provided by charge containment layer **550**. In this instance, if an opposite polarity of charge is provided at the end of nanotube **510**, an attracting force preferably causes nanotube **510** to couple sense contact **520**.

FIG. **8** shows memory cell **500** when only charge profile **563** is provided by charge containment layer **560**. In this instance, if an opposite polarity of charge is provided at the end of nanotube **510**, an attracting force preferably causes nanotube **510** to couple sense contact **530**.

Persons skilled in the art will appreciate that additional sense contacts and charge containment layers may be included in memory cell **500**. Furthermore, memory cell **500** is not just limited to using the polarities illustrated. Memory cell **500** may easily utilize the opposite polarities or a combination thereof. For example charge containment layer **560** may store a positive charge profile while charge containment layer **553** stores a negative charge profile.

FIG. **9** shows memory cell **900** in which a single charge containment layer **950** is included that can hold multiple charge profiles **951** and **952**. In the illustrated embodiment, two charge profiles are included. However, numerous additional charge profiles may be included in charge containment

layer **950**. Charge containment layer **950** stores multiple and distinct bits. Charge containment layer **950** may be, for example, an oxide-nitride-oxide layer.

Charge profiles **951** and **952** may be erased and written to by contacts **961-964**. Persons skilled in the art will appreciate that contacts **961** and **964** may be removed from memory cell **900** without detracting from its operability. Alternatively, additional contacts may be placed around charge containment layer **950** to, for example, store additional bits, erase faster, erase more accurately, write faster, and write more accurately.

Preferably, memory cell **900** operates as follows. Sense contact **920** will receive a signal if only charge profile **951** is present and a charge of an opposite polarity is applied to nanotube **910**. Sense contact **930** will receive a signal if both charge profiles **951** and **952** are present and a charge of an opposite polarity is applied to nanotube **910**. Sense contact **940** will receive a signal if only charge profile **952** is present and a charge of an opposite polarity is applied to nanotube **910**. None of the sense contacts **920**, **930**, and **940** will receive a signal if neither charge profile **951** nor **952** are present. Thus, four states may be determined from the two bits stored in charge containment layer **950**. If a base-four logic system is utilized then a single base-four bit may be read from memory cell **900**. Sense contacts **920**, **930**, and **940** may, for example, be placed above nanotube **910** such that repelling forces from charge profiles **951** and **952** create electrical couplings between nanotube **910** and these sense contacts if the polarity of the charge applied to nanotube **910** is the same as the charges stored in charge containment layer **950**.

FIG. **10** shows memory cell **1000** in which a single single-bit memory cell **1050** is included and written to, and erased by, signals applied to contacts **1051** and **1052**. Memory cell **1000** includes nanotube **1010** that is coupled to conductive retainer **1003** and anchored to base **1001** by non-conductive layer **1002**. Sense contacts **1020**, **1030**, and **1040** are also included.

Memory cell **1000** illustrates the principle that multiple states can be determined from a single charge profile. For example, a SMALL, MEDIUM, and LARGE charge may be stored in charge containment layer **1050**. If a SMALL charge is stored, an appropriate signal is applied to nanotube **1010** then nanotube **1010** preferably electrically couples sense contact **1020**. If a MEDIUM charge is stored, an appropriate signal is applied to nanotube **1010** then nanotube **1010** preferably electrically couples sense contact **1030**. If a LARGE charge is stored, an appropriate signal is applied to nanotube **1010** then nanotube **1010** preferably electrically couples sense contact **1040**. A fourth state can be determined if a signal is applied to nanotube **1010** and none of sense contacts **1020**, **1030**, and **1040** pick up a signal from nanotube **1010**.

Persons skilled in the art will appreciate that conductive sense contacts **1020**, **1030**, and **1040**, may have different dimensions **1091**, **1092**, and **1093** such that nanotube **1010** only couples a single sense contact at any one time. Alternatively, sense contacts **1020**, **1030**, and **1040** may have the same dimensions. In such an embodiment control circuitry (not shown) simply has to determine, for example, which sense contact closest to (or furthest from) charge containment layer **1050** is receiving a signal representative of a signal applied to nanotube **1010** in order to determine the amount of charge that is stored (or is not stored) in containment layer **1050**.

Persons skilled in the art will appreciate that each of contacts **1020**, **1030**, and **1040** may be either nanometer-

scale beams (e.g., nanotubes) themselves or coupled to nanometer-scale beams (e.g., nanotubes) such that nanotube **1010** electrically couples with these nanometer-scale beams instead of contacts **1020**, **1030**, and **1040**. As a result, wear in system **1000** will be minimized since certain nanometer-scale beams exhibit good (e.g., LOW) wear characteristics. Additionally, nanotube **1010** may be attached at both ends to layer **1002** (i.e., mounted to base **1001**), as shown in FIG. **10A**. In such an embodiment, the portion between these two mounted ends is free to move. Mounting nanotube **1010** at both ends increases stability in system **1000** and, as a result, increases the level of control of nanotube **1010**. Persons skilled in the art will appreciate that dimensions **1091**, **1092**, and **1093** will preferably form a pyramid shape if nanotube **1010** is attached at both ends.

Persons skilled in the art will appreciate that two components do not have to be connected or coupled together in order for these two components to electrically interact with each other. Thus, persons skilled in the art will appreciate that two components are electrically coupled together, at least for the sake of the present application, when one component electrically affects the other component. Electrical coupling may include, for example, physical connection or coupling between two components such that one component electrically affects the other, capacitive coupling, electromagnetic coupling, free charge flow between two conductors separated by a gap (e.g., vacuum tubes), and inductive coupling.

Additional advantageous nanometer-scale electromechanical assemblies are described in commonly assigned copending U.S. patent application Ser. No. 10/453,326 (now U.S. Pat. No. 7,199,498) to Pinkerton et al., entitled "Electromechanical Assemblies Using Molecular-Scale Electrically Conductive and Mechanically Flexible Beams and Methods For Application of Same," commonly assigned copending U.S. patent application Ser. No. 10/453,783 to Pinkerton et al., entitled "Nanoelectromechanical Transistors and Switch Systems," and commonly assigned copending U.S. patent application Ser. No. 10/453,373 (now U.S. Pat. No. 7,148,579) to Pinkerton et al., entitled "Energy Conversion Systems Utilizing Parallel Array of Automatic Switches and Generators," which are all hereby incorporated by reference in their entirety and filed on the same day herewith.

From the foregoing description, persons skilled in the art will recognize that this invention provides nanometer-scale electromechanical memory cells and methods for using the same. Persons skilled in the art will appreciate that the various configurations described herein may be combined without departing from the present invention. For example, a magnetic field may be included in the nanometer-scale memory cell **1000** of FIG. **10**. It will also be recognized that the invention may take many forms other than those disclosed in this specification. Accordingly, it is emphasized that the invention is not limited to the disclosed methods, systems and apparatuses, but is intended to include variations to and modifications therefrom which are within the spirit of the following claims.

What is claimed is:

1. A system comprising:

a base;

a nanometer-scale beam coupled to said base having a first portion that is free-to-move; and

a first charge containment layer coupled to said base in the proximity of said first free-moving portion, wherein said charge containment layer is operable to receive, and store, a first charge profile without moving said

nanometer-scale beam and said nanometer-scale beam is not operable to physically touch said first charge containment layer.

2. The system of claim **1**, wherein said nanometer-scale beam is a nanotube.

3. The system of claim **1**, wherein said nanometer-scale beam is a single walled carbon nanotube, a multi-walled carbon nanotube, a boron carbide nanotube, or a carbon nitride nanotube.

4. The system of claim **1**, wherein said nanometer-scale beam is a tube-shaped, electrically conductive and mechanically flexible, molecule.

5. The system of claim **1**, wherein said nanometer-scale beam is a rod-shaped, electrically conductive and mechanically flexible, molecule.

6. The system of claim **1**, wherein said nanometer-scale beam is a group of bonded, electrically conductive and mechanically flexible, molecules.

7. The system of claim **1**, further comprising:
a first sense contact placed in the proximity of said first free-moving portion.

8. The system of claim **1** wherein said charge profile is stored in said first charge containment layer.

9. The system of claim **1**, further comprising:
a first transistor having an emitter, base, and collector terminal, wherein said emitter terminal is coupled to said charge containment layer;
a control circuit coupled to said base terminal; and
a first WRITE/ERASE contact coupled to said collector terminal.

10. The system of claim **1**, further comprising:
a transistor having an emitter, base, and collector terminal, wherein said collector terminal is coupled to said charge containment layer;
a control circuit coupled to said base terminal; and
a first WRITE/ERASE contact coupled to said emitter terminal.

11. The system of claim **1** wherein said nanometer-scale beam is coupled to said base via a mounting assembly, wherein said mounting assembly further comprises:

a conductive layer coupled to said nanometer-scale beam.

12. The system of claim **11**, wherein said mounting assembly further comprises:

an isolation layer coupled between said conductive layer and said base.

13. The system of claim **1**, wherein said nanometer-scale beam is fixed at one end.

14. The system of claim **1**, wherein said nanometer-scale beam is fixed at both ends.

15. The system of claim **1**, wherein said nanometer-scale beam comprises a second portion that is free-to-move, said nanometer-scale beam fixed to a mounting assembly between said first and second free-moving portions.

16. The system of claim **1**, further comprising:
a TEST contact placed in the proximity of a resting location of said first free-moving portion; and
a sense circuit coupled to said TEST contact that senses when said first free-moving portion is in said resting location.

17. The system of claim **1**, further comprising:
a voltage source coupled to said nanometer-scale beam, wherein said charge profile having a first polarity, said voltage source having a second polarity, and said charge profile is stored in said first charge containment layer;
a first sense contact placed in the proximity of said first free-moving portion; and

15

a sense circuit that senses when said first free-moving portion electrically couples said first sense contact.

18. The system of claim 17, wherein said first and second polarities are of opposite polarities.

19. The system of claim 17 wherein said first and second polarities are of the same polarity.

20. The system of claim 17, further comprising:
a second charge containment layer in the proximity of said first free-moving portion being able to store a second charge profile.

21. The system of claim 17, further comprising:
a second sense contact placed in the proximity of said first free-moving portion.

22. The system of claim 21, wherein said free-moving portion electrically couples to said first sense contact when said first charge profile comprises a first amount of charge and said free-moving portion electrically couples to said second contact when said first charge profile has a second amount of charge, wherein said first amount of charge is not equivalent to said second amount of charge.

23. The system of claim 1, further comprising:
a second charge containment layer placed in the proximity of said first free-moving portion being able to store a second charge profile.

24. The system cell of claim 1 further comprising:
a first sense contact; and
a sense circuit that senses the rate of contact between said first free-moving portion and said first sense contact for a period of time.

25. The system of claim 24 wherein said first charge profile is stored in said first charge containment layer, said first charge profile comprising a first amount of charge that causes said first-free moving portion to contact said first sense contact at a first contact rate.

26. The system of claim 25 further comprising:
a control circuit, wherein said control circuit changes said first amount of charge to a second amount of charge and said first free-moving portion contacts said first sense contact at a second contact rate, said second contact rate being different from said first contact rate.

27. A system comprising:
a base;
a nanometer-scale beam coupled to said base having a first portion that is free-to-move;
a first charge containment layer coupled to said base in the proximity of said first free-moving portion, wherein said charge containment layer is operable to receive, and store, a first charge profile without moving said nanometer-scale beam and said nanometer-scale beam is not operable to physically touch said first charge containment layer; and
a first sense contact placed in the proximity of said first free-moving portion and exposed to a magnetic field.

28. A system comprising:
a base;
a nanometer-scale beam coupled to said base having a first portion that is free-to-move;
a first charge containment layer coupled to said base in the proximity of said first free-moving portion, wherein said charge containment layer is operable to receive, and store, a first charge profile without moving said nanometer-scale beam and said nanometer-scale beam is not operable to physically touch said first charge containment layer;
an isolation layer;
a first WRITE/ERASE contact placed between said isolation layer and said charge containment layer; and

16

WRITE/ERASE electrical signals that are provided to said WRITE/ERASE contact, wherein said WRITE/ERASE electrical signals write said first charge profile into said charge containment layer.

29. The system of claim 28 further comprising a control circuit that provides said WRITE/ERASE electrical signals.

30. A system comprising:
a base;
a nanometer-scale beam coupled to said base having a first portion that is free-to-move;

a first charge containment layer coupled to said base in the proximity of said first free-moving portion, wherein said charge containment layer is operable to receive, and store, a first charge profile without moving said nanometer-scale beam and said nanometer-scale beam is not operable to physically touch said first charge containment layer, wherein said charge profile is stored in said first charge containment layer;

an isolation layer;
a first WRITE/ERASE contact placed between said isolation layer and said charge containment layer; and
WRITE/ERASE electrical signals that are provided to said WRITE/ERASE contact, wherein said WRITE/ERASE electrical signals erase said charge profile from said first charge containment layer.

31. The system of claim 30 further comprising a control circuit that provides said WRITE/ERASE electrical signals.

32. A system comprising:
a base;
a nanometer-scale beam coupled to said base having a first portion that is free-to-move;

a first charge containment layer coupled to said base in the proximity of said first free-moving portion, wherein said charge containment layer is operable to receive, and store, a first charge profile without moving said nanometer-scale beam and said nanometer-scale beam is not operable to physically touch said first charge containment layer;

a first transistor having an emitter, base, and collector terminal, wherein said emitter terminal is coupled to said charge containment layer;
a control circuit coupled to said base terminal; and
a first WRITE/ERASE contact coupled to said collector terminal, wherein said first transistor comprises a nanometer-scale transistor.

33. A system comprising:
a base;
a nanometer-scale beam coupled to said base having a first portion that is free-to-move;

a first charge containment layer coupled to said base in the proximity of said first free-moving portion, wherein said charge containment layer is operable to receive, and store, a first charge profile without moving said nanometer-scale beam and said nanometer-scale beam is not operable to physically touch said first charge containment layer;

a transistor having an emitter, base, and collector terminal, wherein said collector terminal is coupled to said charge containment layer;

a control circuit coupled to said base terminal; and
a first WRITE/ERASE contact coupled to said emitter terminal, wherein said transistor comprises a nanometer-scale transistor.